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PHASE I SMALL BUSINESS INNOVATION RESEARCH (SBIR) PROGRAM

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Mail Address: 4509 Runway St, Simi Valley, CA 93063
Principal Investigator: Mr Herb Chelner

INTERIM REPORT

PERIOD 1/31/2002 TO 4/31/2002

EMBEDDED SENSOR TECHNOLOGY FOR SOLID ROCKET MOTOR HEALTH MONITORING

MICRON REPORT NO: 02-221

ABSTRACT

Report developed under SBIR contract for topic A01-166 'Embedded Sensor Technology for Solid Rocket Motor Health Monitoring'. This interim report outlines the significant progress achieved during this reporting period. Results from constant load tests indicate that the current build standard of sensor is stable and does not creep when under 90% full scale tensile load for over four months. The tests are continuing. Sensors and loggers have been manufactured and delivered and laboratory analog samples cast and successfully tested. The recorded data is good and will be analyzed to establish prognostic parameters for use in future phases of the work

SECTION 1 - Program Milestones

An SBIR kickoff meeting took place at the Propulsion and Structures Directorate of the U.S. Army Aviation and Missile Command (AMCOM) on the 14th March 2002. Representatives from MICRON, DASCOR, and AMCOM Propulsion and Structures and Engineering Directorates were in attendance. MICRON Instruments personnel presented their planned approach to achieving the goals set forth in the Department of Defense FY 2001 Program Solicitation 2001.2. The Phase I Objectives listed in the solicitation were as follows:

Phase I Objectives:

- Perform literature review, development, and investigation to select one or two most promising sensor technologies to be used as an embedded sensor for monitoring stress and/or strain in solid rocket motor bondlines.
- Establish temperature and pressure sensitivity, long-term measurement stability and chemical compatibility, and sensor calibration procedures.
- Develop associated prognostics (i.e. what does the sensor reading mean w/r/t solid rocket motor structural and ballistic integrity).
- Establish integration into RRAPDS system (provide capability for continual or intermittent monitoring of sensor readings through RRAPDS or a data acquisition scheme compatible with RRAPDS).

Through the results of literature review (discussed in section 2) and past sensor development (funded largely by Micron Instruments and other NATO countries), it was shown that an imbedded stress transducer would meet the majority of the desired features and would provide data addressing the most critical, and yet most difficult parameter for evaluation in a solid rocket motor health monitoring system – transient bondline stress. Sensor features such as operational temperature range, accuracy, sensitivity, non-intrusiveness, long term measurement stability, versatility, robustness for installation, safety, low power requirements, ease of calibration, material compatibility, low corrosion sensitivity, and cost were all given consideration. A cooperative laboratory study was conceived with AMCOM personnel, to obtain valuable data focused upon achieving the Phase I objectives.

The first batch of six sensors and two data loggers have been delivered for installation into laboratory analogs and the required training session to use the associated data logger software has been successfully completed. The following sensors were delivered: Model No. #150584 (as shown in Figure 1.)

Serial No	Sensitivity (mV)	Static Error Band (%FS)
60716	18.83	0.176
60717	21.48	0.236
60718	21.86	0.093
60719	19.30	0.078
60720	20.46	0.225
60721	21.06	0.081

The following data loggers were delivered: Model No MI 1008-1 (shown in Figure 2.)

Serial No.	**V_{offset} (V)**	**Gain**
9823-0006	2.04/1.02	158.5/19.81
0107-0004	2.04/1.32	153.3/19.43

The given values are the average of the four stress channels/average of the four temperature channels. The design and manufacture of the high accuracy strain gage test system is on schedule and will be complete by the end of June. This equipment will be used to precision match the strain gages to be used for the improved sensors to be used in later phases of this work

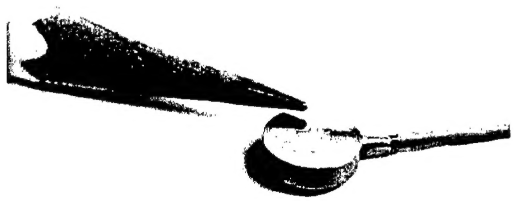

Figure 1. Model No. 150584 Sensor

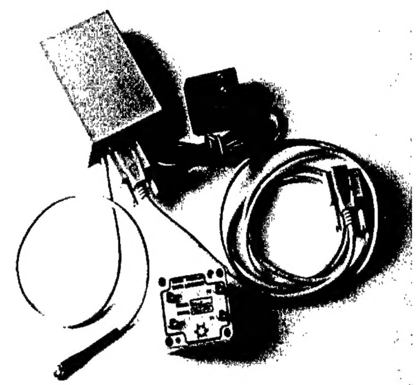

Figure 2. Model No. MI 1008-1 Logger

SECTION 2 - Review of Sensor Technology

A critical review of published papers (a list is given in Appendix A) has been undertaken. The reported results from trials using Micron embedded sensors have been assessed to establish the achieved performance of the technology. The results can be characterized into two separate areas: Sensor performance and Installation Effects.

2.1 Sensor Performance

The majority of sensors performed as calibrated with properties as reported on the associated calibration sheets. A reliability problem with the robustness of the plug/socket used to attach the sensor cable to the bridge completion unit and to the logger was responsible for intermittent continuity. This problem has been addressed and more robust electrical connectors will be used for Phase II sensors.

A requirement to seal the sensor to ambient pressure was also established when high-pressure calibration trials were undertaken on 'bare' sensors and a number of the units leaked and equilibrated to zero load. To overcome this problem it has been recommended that a scheme be developed to hermetically seal the sensor as part of the Phase II submission. This would also improve the sensor stability and long term accuracy. Work is also in progress at AMCOM using

the supplied sensors to establish temperature and pressure sensitivity over the temperature range -50°F to +150°F and pressures up to 100 psi. The results will be discussed in the Final Phase I report.

2.2 Installation Effects

It is essential that the sensor be correctly mounted in the test sample. To make the most accurate stress measurement, the mounting should be as non-compliant as possible (i.e. rigid with respect to the propellant grain). Still, the most optimal method of installation may depend upon the particular design and manufacturing sequence of the solid rocket motor, its own structural and thermal requirements, and the location in the motor for which the stress is to be measured. One objective of the design of the laboratory analog was to address whether the effect of installation into a semi-rigid insulation could be tolerated and whether the effect of insulation compliance could be compensated for within the sensor calibration. In this way, more options may be provided to the motor manufacturer to achieve compromise between the needs of the motor, the required manufacturing operations, and proper sensor installation.

A second requirement for accurate stress measurement is that the propellant must be well bonded to the sensor or through its various interfaces. Cleanliness is essential to facilitate good bonding. Long term chemical compatibility of all the components must also be assured for both safety and structural integrity. In the laboratory analog design chosen for Phase I, the sensor has been installed at the interface between the liner and insulation. The liner material is approximately 0.020 inches thick, and is composed of the same polymeric base material as the propellant (hydroxyl terminated polybutadiene). Pathfinder analogs were cast and liner peel testing was completed to ensure that liner formulation and cure were adequate to achieve a good bond to the surface of the sensor. Each rocket motor/laboratory analog sample geometry can be different with unique problems for egress and cable management with respect to installation. Past experience and recommended practice is being recorded and will be included as part of the Final Phase I report. Methods of cable management and egress from a tactical motor will be developed and tested as part of the Phase II work items.

SECTION 3 - Long-Term Measurement Stability

Calibration checks of the sensor after casting of the propellant grain is not possible, therefore it is essential that the units used for long term health monitoring are accurate and stable. Any creep or zero shift in the sensor output would be indistinguishable from changes in the measured bond stress. Long term changes in balance with no sensor stress have also been run and were found to be acceptable. To test the stress stability of the current system a cantilever constant load test consisting of a static load applied to the sensor diaphragm was initiated and has been running for 18 weeks. The loading fixture is shown in Figure 3 and a local view of the sensor under tension load shown in Figure 4. The stress was applied to the sensor via a hard rubber interface and hanging weights. Extra care was used to ensure that the bonded surface area was limited to be that of the active surface area of the sensor diaphragm.

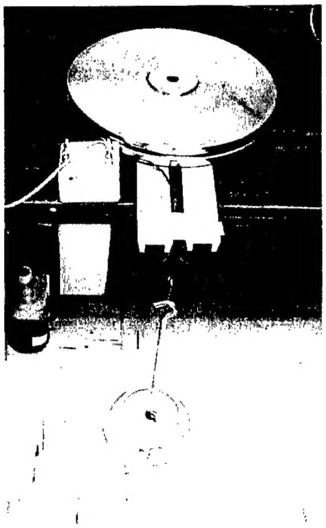

Figure 3.

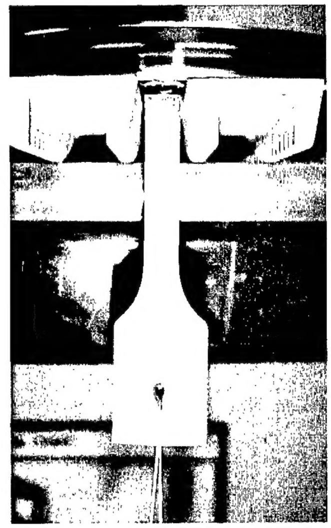

Figure 4.

The most recent download of the results are given in Figure 5 which shows that the variation of output is 242 ± 2 mV (series 1) for the load which is limited by the accuracy of the logger, and the ambient temperature variations (series 2). An outline of the results for the test are given below. There is no significant indication of creep in the results for the test period of 180k minutes and the test is continuing.

Date	Start(mV)	Finish (mV)
31st December	240/160	240/160
31st Dec to 22nd Jan	240/162	242/163
22nd Jan to 19th Feb	242/170	242/176
20th Feb to 24th April	241/175	244/172

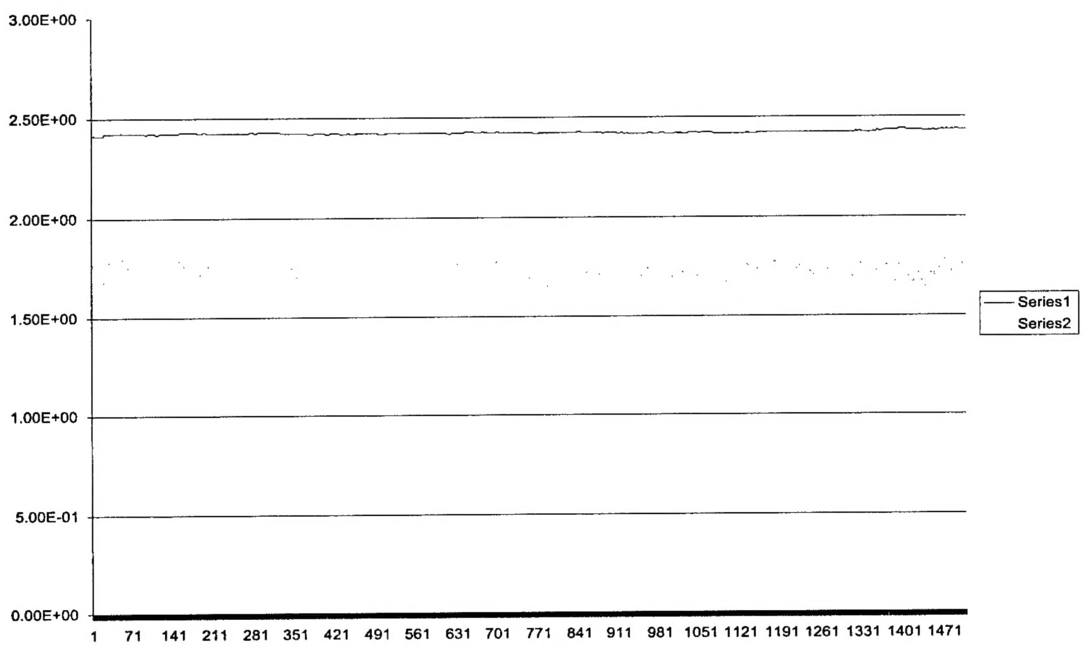

Figure 5. Long Term Measurement Stability Experiment

SECTION 4 - Evaluation of Chemical Compatibility

One of the concerns which must be addressed for any embedded sensor in a solid rocket motor is whether the sensor itself is compatible with the chemistry of the propellant, the liner, and the insulation in the bondline. Of these, the propellant will contain the most caustic constituents.

In typical solid rocket motor applications, there will be one of two common families of materials which must be considered; and these are associated with the type of propellant system used in the rocket motor. The two types of systems can be generally described as either composite or double base propellants. In the former, the propellant is composed of rigid oxidizer and fuel particles embedded in an inert polymeric matrix (approximately 84-91% solids by weight). In the latter, the propellant is composed of nearly all polymeric material, some of which may be energetic, and may also contain some level of solids loading. Composite propellants normally use ammonium perchlorate or ammonium nitrate as their oxidizing agents; both are materials which can go into solution and produce corrosive by-products in the presence of significant moisture. Double base propellants, by comparison, can contain many types of chemical explosives, such as nitroglycerin. Both families can contain trace elements such as plasticizing agents, ballistic modifiers, and stabilizers; which are subject to diffusion processes, and which may in fact have long term effects on sensors installed in motors. An exhaustive evaluation of this issue could not be addressed within the scope of a Phase I effort. Fortunately the double base propellant motors, due to the high strain capability of their formulations, are much less susceptible to bondline stress failures (their aging mechanism is more governed by loss of chemical stabilizer through depletion reactions). For this reason, a composite propellant formulation was chosen to be used in the laboratory studies (HTPB/AP/AL).

An evaluation of sensor construction and materials can be used to infer the inherent chemical compatibility and resistance to corrosion. The sensor main cavity is composed of either 6Al-4V titanium or 17-4 precipitation hardened stainless steel. Both materials are relatively impervious to attack from hydrochloric or nitric acids; one by-product of ammonium perchlorate or ammonium nitrates in solution. The lead wire exiting the sensor is covered with a 0.010 inch thick, Teflon insulation, which is also not expected to be in any measurable way affected by propellant constituents. While this version of the sensor is not hermetically sealed, any significant moisture penetration into the sensor cavity is not expected; and likely would result in far worse damage to the motor itself, than to the embedded sensor.

SECTION 5 - Sensor Calibration Procedures

As discussed in previous sections, a particular laboratory analog geometry, propellant material, and construction approach was selected, to be consistent with the objectives of the Phase I study, and to provide laboratory test articles for use by AMCOM. Despite the fact that the most accurate installation of the sensor would be placement directly onto the metal substrate (motor case or bond tab), it was of equal importance that other installation methods be assessed. Previous investigations, described in the literature, had not fully characterized the tolerance to and the effects of, insulation compliance. For these reasons, and to achieve simplicity in casting tooling design, AMCOM personnel chose to install sensors into the insulation substrate which

made up the structure of the bondline. The insulation material was Kevlar-filled PolyIsoprene; for which cure, stiffness, and adherence properties were assessed in separate studies. The analog casting tooling, and sensor installation are shown in Figures 6 and 7, respectively. The insulation was machined to contain a small cavity and slot in which the sensor could be embedded and bonded in place with epoxy (FUSOR 305, Lord Chemical). This installation method ensured that the sensing diaphragm would be located precisely at the insulation-to-liner interface.

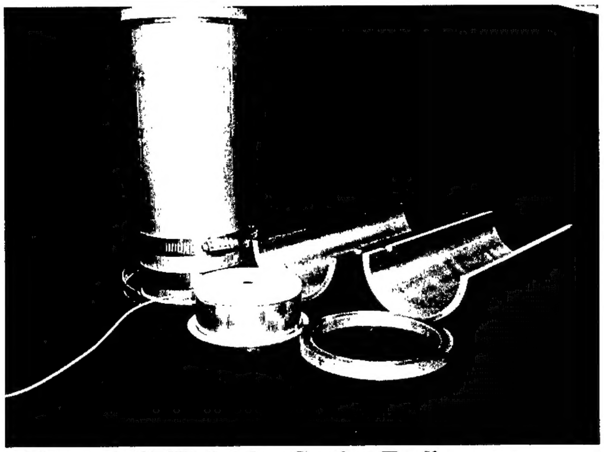

Figure 6. SBIR Analog Casting Tooling

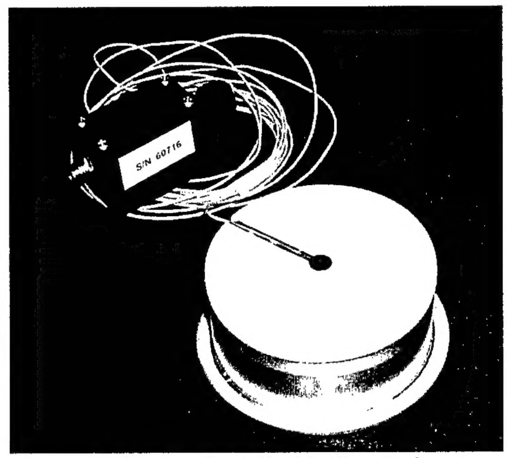

Figure 7. Sensor Installed in Insulation

The choice of installation method, while most convenient for analog casting, also meant that considerable effort must be expended to perform calibrations of the sensors which accounted for insulation compliance. To achieve this, a series of tools were fabricated. MICRON sent to AMCOM a factory calibration fixture, to calibrate the sensors using dry nitrogen gas pressure (0 to 100 psi). An additional calibration chamber was fabricated, so that the same sensors could be re-calibrated after being installed into the insulation on the end tab. In this way, the effect of insulation compliance could be measured and accounted for in data reduction for combined loads testing of the analogs. Shown in Figure 8 are the calibration station and test fixtures.

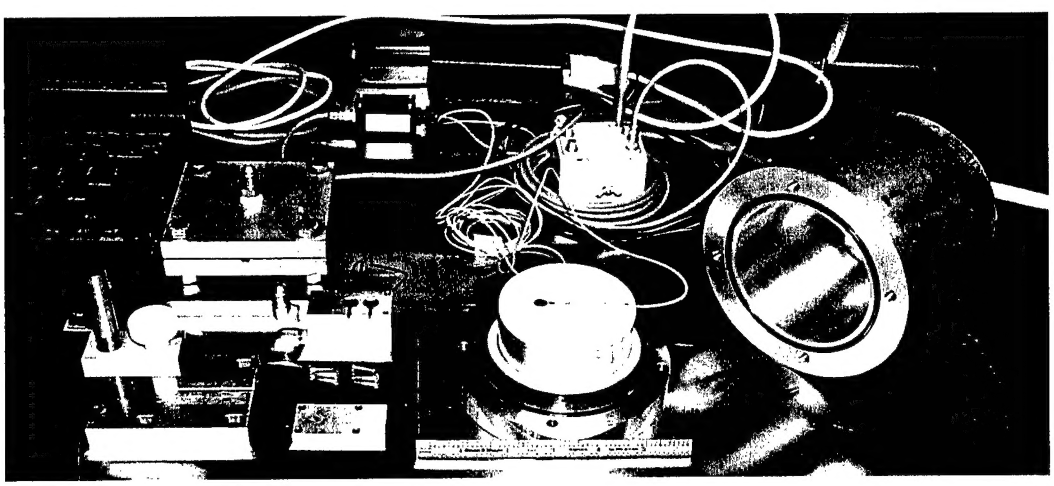

Figure 8. Sensor Calibration for Insulation Compliance

Shown in Figure 9 is a comparison of calibration curves for sensors #60718 and #60719, which show that the factory calibration fixture and AMCOM calibration fixture both provide similar data, and that when embedded in the insulation, the effects of compliance may either increase or diminish with pressure. One possible explanation for this phenomenon is that the two sensors were made, respectively, of stainless steel and titanium. Perhaps the stiffness of the sensor itself may contribute to the difference in response. Obviously, more evaluations of this issue are needed. Nonetheless, the results thus far give good confidence that the effect of insulation compliance may be accounted for on a case-by-case basis, prior to propellant casting.

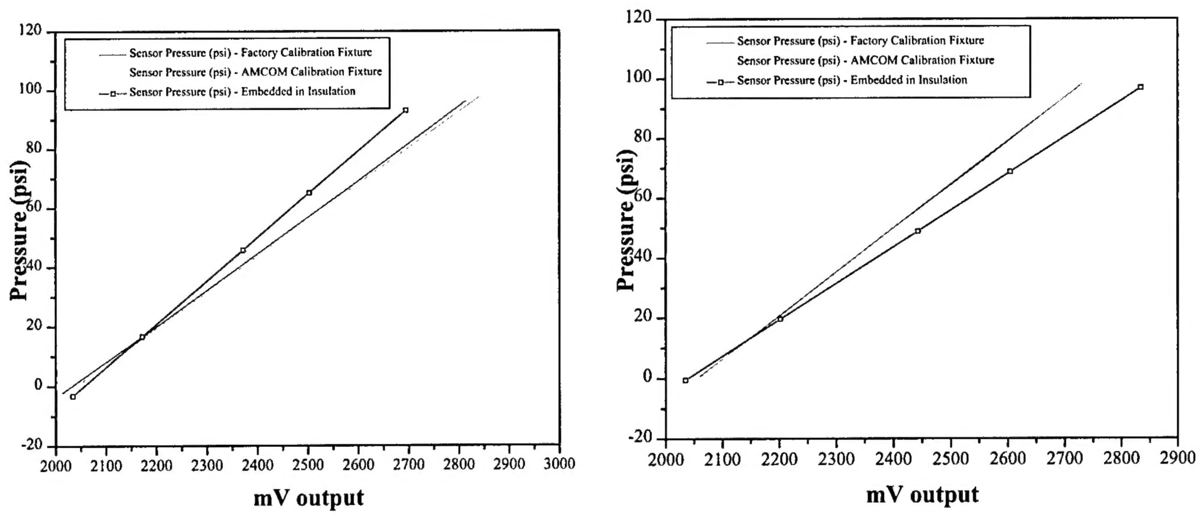

Figure 9a. and 9b. Respective Calibration Curves, Accounting for Insulation Compliance

SECTION 6 – Development of Associated Prognostics

In order to accomplish this objective, AMCOM personnel conceived and implemented a series of tests using the cast laboratory analog. The first two tests of the series have recently been successfully completed, and are reported herein. The concept for the testing was to devise a laboratory test article, which might be subjected to combined loads and cyclic testing, with known and controlled boundary conditions, while simultaneously measuring global loads and displacements. In this way, the articles might be subject to realistic and complex loading scenarios and the embedded sensors might be rigorously challenged for accuracy and sensitivity. The testing is to take place with specimens oriented at angles ranging from 0° (pure tension) to 90° (simple shear). Through finite element analysis of the analog geometry when subject to asymmetric loads, the stress distribution and its expected magnitude at the bondline are known. The combination of measurement of global loads and displacements, along with stress analysis provides means to validate sensor performance. The detailed stress analyses have been completed for the analogue configuration by AMCOM, and will be documented in the final report. The following paragraphs detail the preliminary results of testing analogs 1 and 2.

6.1 Analogue Fabrication

The first two analogs were cast and curing by AMCOM personnel during the week of 03 through 11 APR 02. After bonding the insulation in place onto an end tab, the insulation is machined, the sensor bonded, and a 24 hour cure cycle (+140°F) imposed to dry out the insulation and fully cure the epoxy. Liner is mixed, manually applied by brush, and pre-cured for 24 hours. Prior to assembly into the casting tooling, a thin "wet coat" of liner is applied, to ensure the best propellant-to-liner bond. Propellant is mixed and vacuum cast, and the analogs are cured for six (6) days at +140°F. Following removal from the curing oven and a 24 hour cool down period, the analogues are de-tooled are prepared for testing.

The configuration of the analog is shown schematically in Figure 10. It may be seen that the test geometry is a right circular cylinder, with a height to diameter ratio of approximately 1. This design, when tested in combined loads or cyclic tension, produces a stress state at the bondline, which is highly constrained and multi-axial; similar to that in a rocket motor. However, one advantage is that unlike a rocket motor, stresses may be induced mechanically (in a tensile test machine), rather than thermally; thus negating the complexity of thermo-viscoelastic material behavior. One modification was made to the specimen that is not shown in the schematic. After stress analysis, it was determined that large stress concentrations existed at the exterior circumference of the specimen, at the bondline interface. To reduce the magnitude of these, a circumferential stress relief slot (0.30 inch depth) was cut into the insulation, as will be illustrated in later figures.

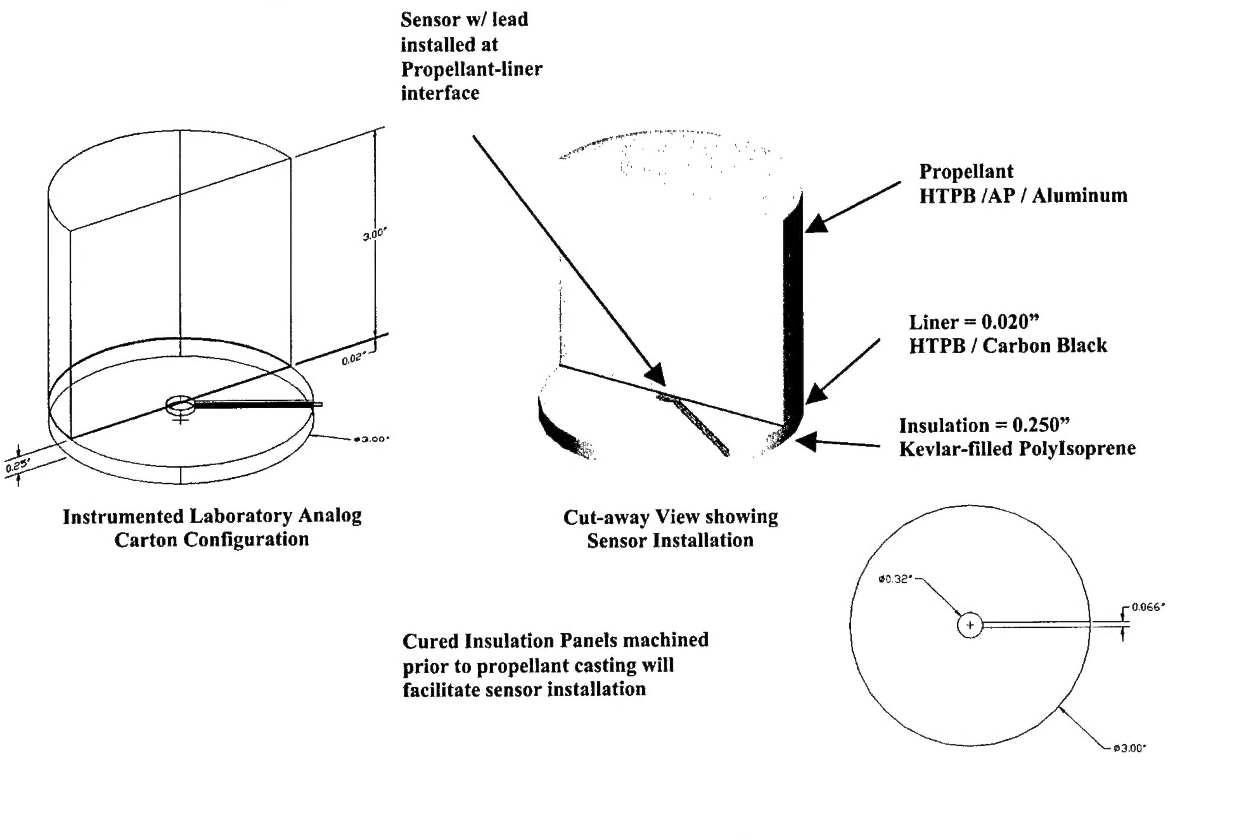

Figure 10. SBIR Analog Configuration Drawing

The sequence of fabrication steps for an analogue are illustrated in Figure 11, which also demonstrates that that much of the process requires tactile contact and could lead to some variation in final product. In order to assess any potential for this, a certain amount of the propellant from each casting will be cured separately for quality assurance testing of mechanical properties. Also, liner "peel boat" witness samples are cast and tested to verify liner cure and bond quality. During the cure process, post-cure cool down, and de-tooling, embedded sensors were logged to record the build-up of cure stress and any stress induced by de-tooling. This data is currently being reduced to engineering units.

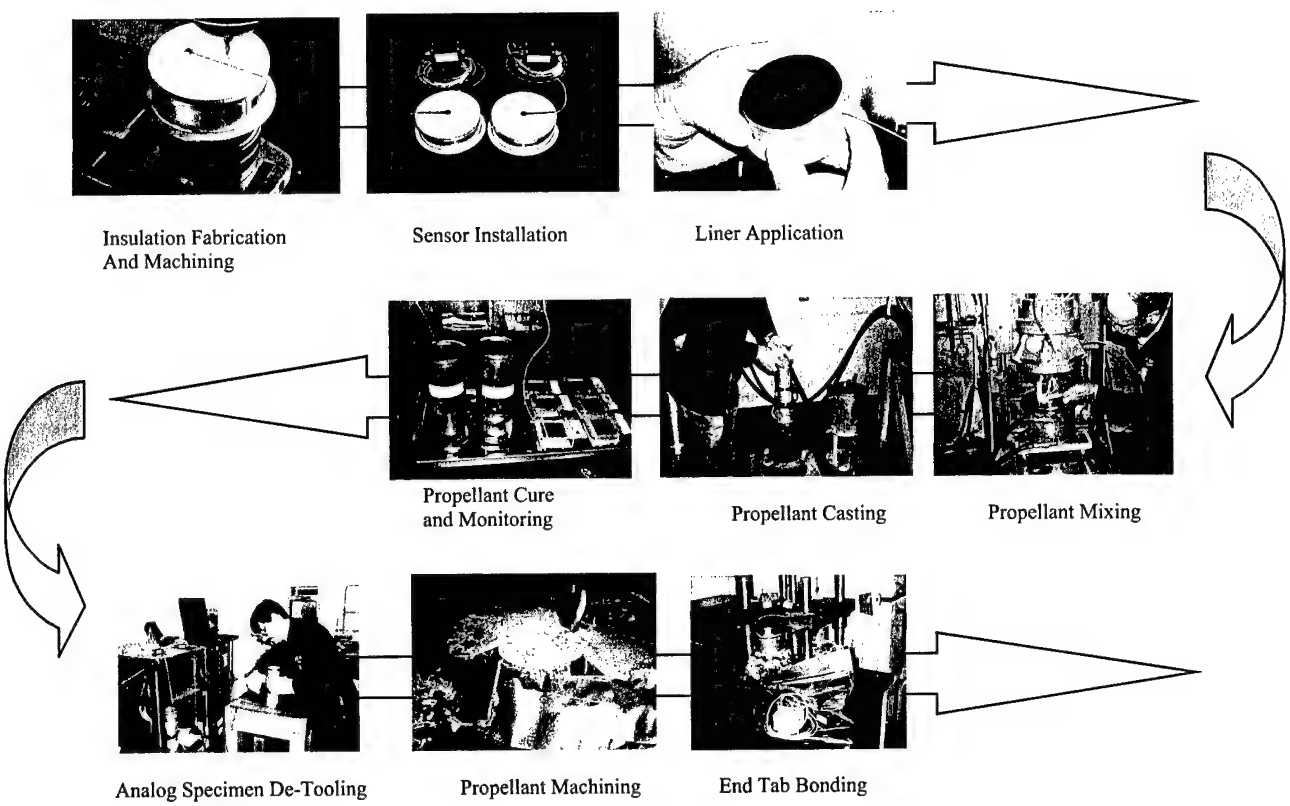

Figure 11. Fabrication Steps for SBIR Analog Specimens

6.2 Preliminary Test Results

The first two analogs, designated as #1 and #2, were fabricated with sensor serial numbers #60716 and #60717, respectively. A complex load sequence was implemented, in which each analog was subjected to a series of 5 load cycles, followed by constant strain for 10 minutes (stress relaxation), followed by 5 cycles, followed by constant strain, … etc. The sequence was repeated in such a way that the strain magnitude in each step was increased 1%, 2%, 3%, ..etc.; up to failure. The global load and displacement were monitored through computer data acquisition, such that the sensor readings and global measurements could be compared after the test. Analog #1 was subjected to pure tension (0° orientation) and Analog #2 was subjected to a combined tension-shear load sequence (45° orientation). A rigid linear bearing test fixture was

fabricated and installed in the INSTRON tensile test machine, to ensure that the boundary conditions would be controlled throughout each test; consistent with those imposed in the finite element stress analysis. The test fixture and Analog #2 are shown in Figure 12 for illustration.

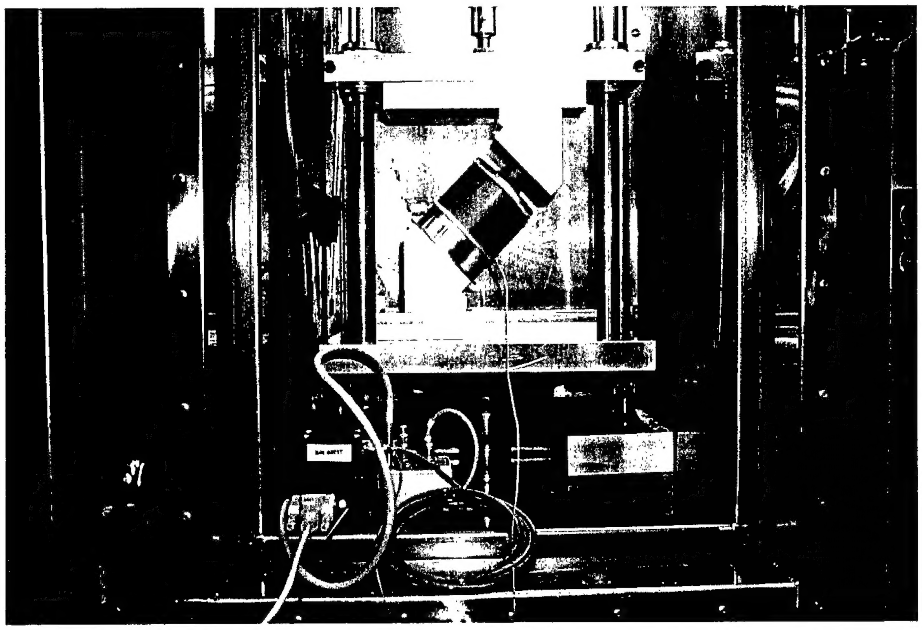

Figure 12. Analog #2 Installed in Rigid Linear Bearing Test Fixture

Test results for Analog #1 and #2 are shown, respectively, in Figures 13 and 14, which also illustrate the complex load sequence. In Figure 13, it is seen that the sensor output follows the nominal stress sequence, defined as the remote load normalized by effective cross-sectional area. More importantly, the sensor capture both the failure event and its location. While the global load still indicates some residual strength capability in the analogue, the sensor indicates near-zero stress. Post –test dissection of the article showed that failure had initiated cohesively in the propellant and in close proximity to the bondline.

Similar results are illustrated by Figure 14 for the tension-shear test. Good correlation results between the sensor and global load measurement, up until the initiation of failure. Unfortunately, the analog was installed into the test fixture with the cable exiting the bondline on the tension side. This lead to a premature failure of the sample, remote from the sensor. As can be seen in Figure 15, the failure occurs at the external perimeter rather than interior to the bondline. Figure 15 also illustrates the insulation flap (stress relief) described in previous sections. Still, the sensor correctly records the fact that there is residual capability internal to the analogue. This test sequence will be repeated with Analog #3, with the cable exiting the sample on the compression side. An additional improvement to the test is that the sensor will now be offset from center, closer to the region of maximum shear stress. Comparison of results between tests will further development of prognostics.

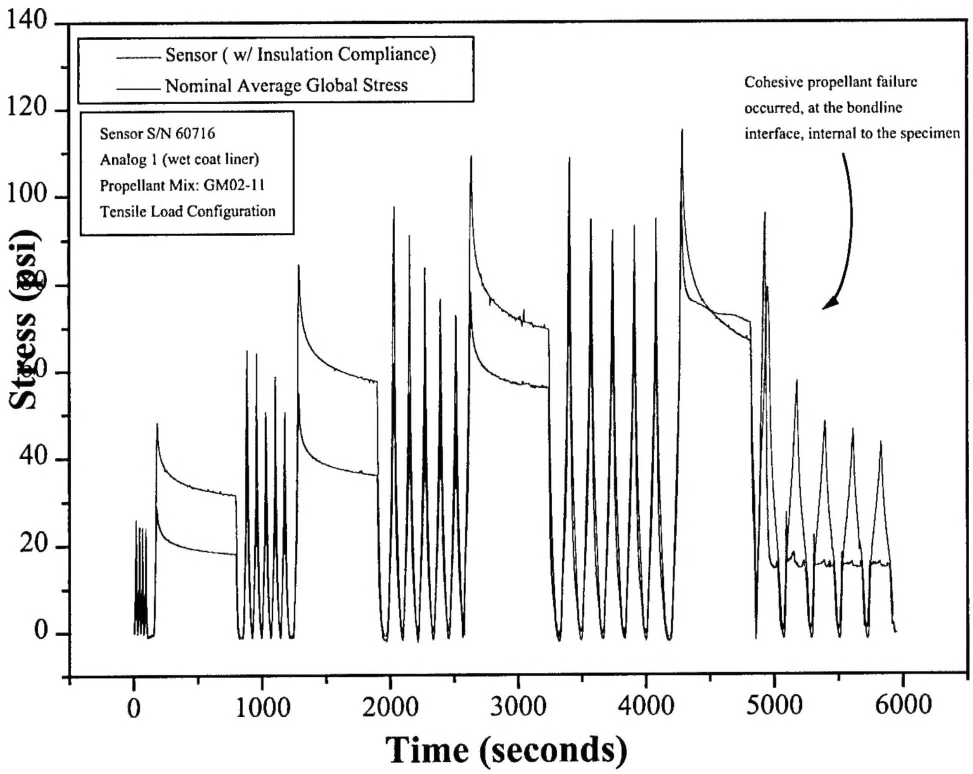

Figure 13. Test Results for Analog #1 (Pure Tension)

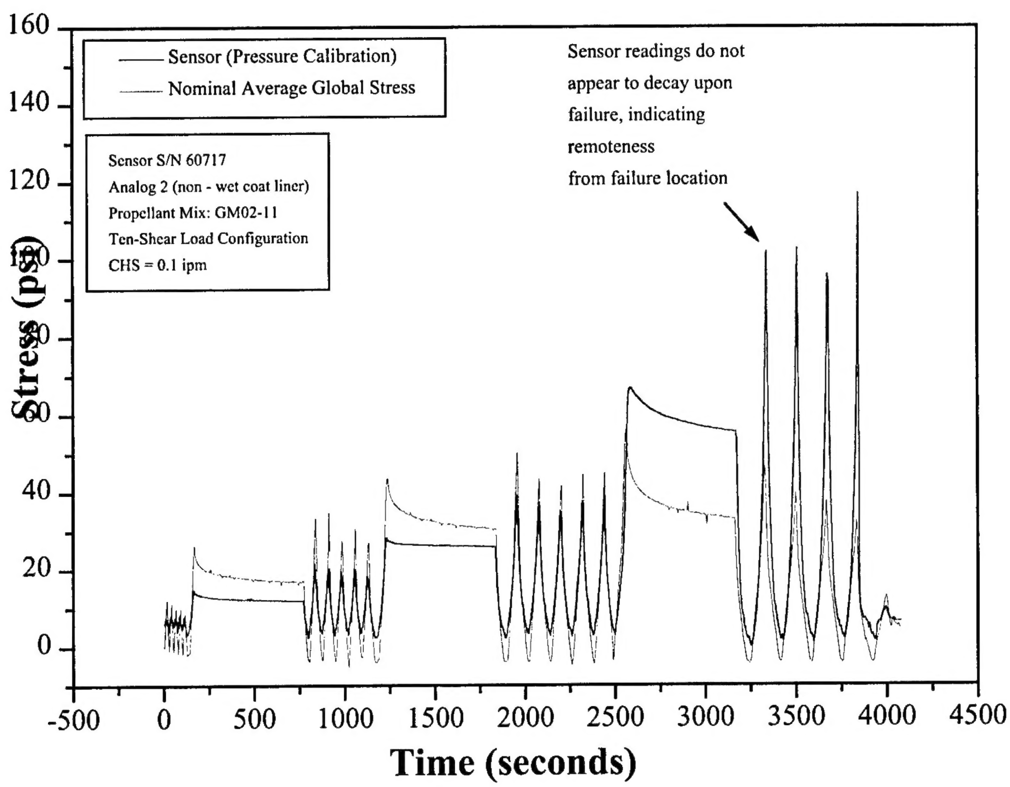

Figure 14. Test Results for Analog #2 (Tension-Shear)

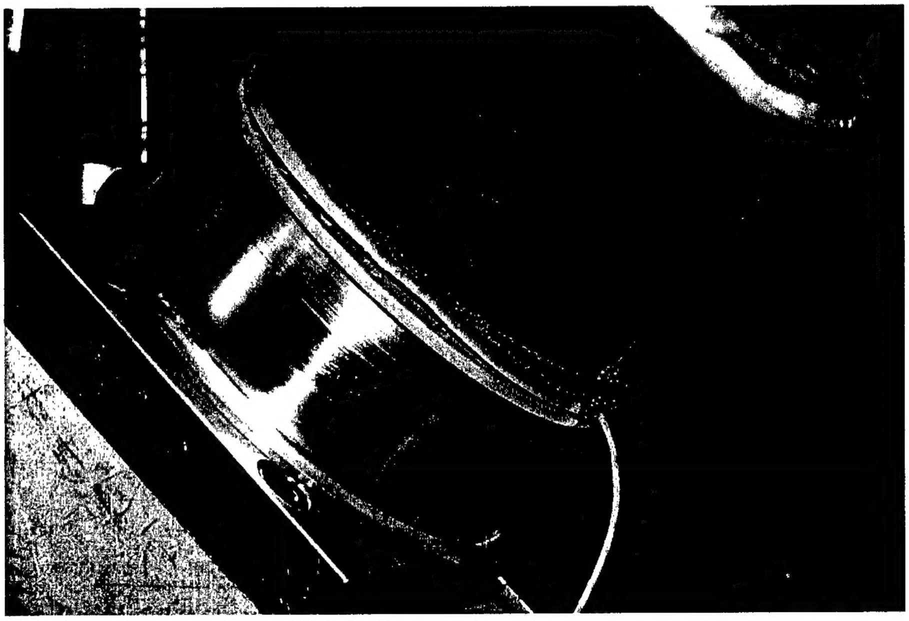

Figure 15. Detail View of Analog #2 during Tension-Shear Test

SECTION 7 - Program Schedule and Milestones

Figure 16 illustrates the detailed program schedule and milestones, and indicates that all objectives are being met or exceeded at this time. No program delays or shortfalls are currently anticipated.

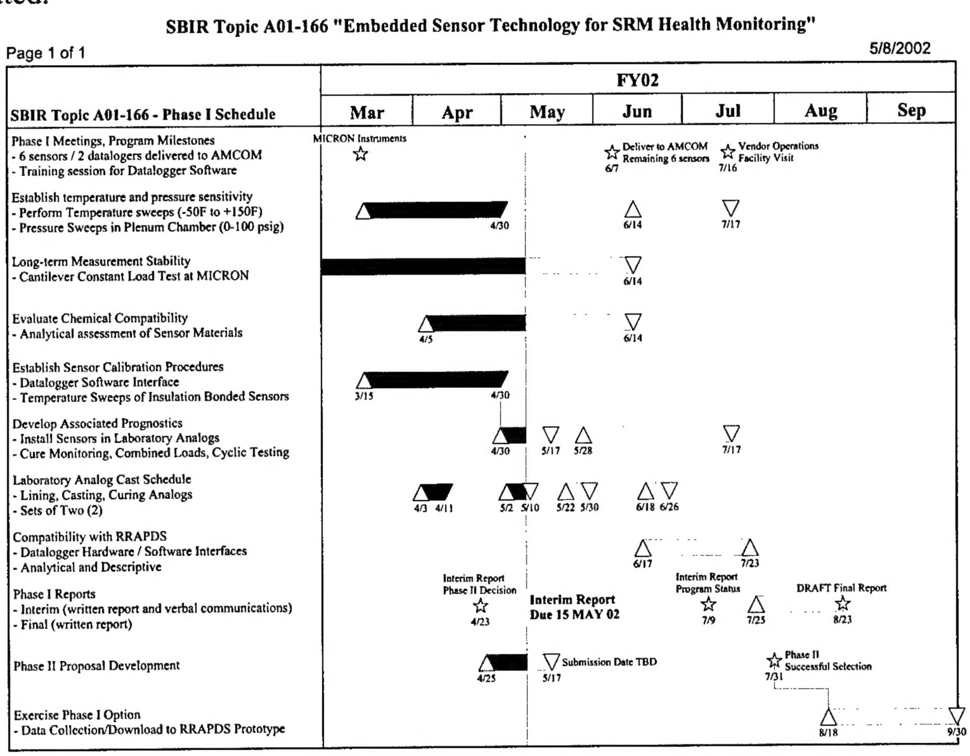

Figure 16. Detailed Program Schedule and Milestones

APPENDIX A

Sensor Related Papers:

a) Improvements in rocket motor life instrumentation.
E C Francis et al, JANNF S&MB Meeting (Dec 1995)

b) Stress Measurement in Solid Rocket Motors.
H J Buswell, 18th Transducer Workshop, RCC (June 1995)

c) Service Life Prediction Methodologies.
Final Reports TTCP KTA 4-14 (1996)

d) Miniature sensor for measuring solid grain rocket motor case bond stress.
H Chelner et al, Paper 25 AGARD Conference Proceedings 586 (May 1997)

c) Service Life Prediction Using Stress Gage Technology and Nonlinear viscoelastic analysis.
F C Wong, Paper 26 AGARD Conference Proceedings 586 (May 1997)

e) Instrumented Service Life Programme for the Pictor Rocket Motor.
S Y Ho, Paper 28 AGARD Conference Proceedings 586 (May 1997)

f) Bond Line Stress Transducers Effectiveness in Measuring Crack Formation in Solid Propellant Analog Motors.
R W Pritchard, JANNAF JPM (1998)

g) Failure Analysis of Rocket Motors on Pressurization
Final Reports TTCP KTA 4-23 (1999)

h) Characterisation and Use of Bond Stress Sensors in Tactical Rocket Motors.
H J Buswell, AIAA Paper #2000-3139 JPC (2000)